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Modelling and simulation of adsorption refrigeration system using low grade thermal energy

#1Piyush Patil, #2 Anindita Roy, #3 H.U.Tiwari

[1]Php1906@gmail.com
[2] Anu.energy@gmail.com
[3]sharvay12 @rediffmail.com

#1PG Student, Department of Mechanical engineering, Pimpri-Chinchwad college of engineering, Nigdi, Pune 44.
#2Associate Professor,Department of Mechanical engineering,Pimpri-Chinchwad college of engineering,Nigdi,Pune44.
#3Professor, Department of Mechanical engineering,Pimpri-Chinchwad college of engineering,Nigdi,Pune 44

ABSTRACT

Increasing demand for air conditioning and global environmental changes are the most prominent reasons to pay attention towards effective utilization of low grade thermal energy. Adsorption systems are driven by low grade thermal energy which are alternatives to the conventional refrigeration systems, hence adsorption systems are more popular from the last two decades. Due to their intermittent working principle, the COP of the system is 0.3-0.5 which is very low compared to the conventional refrigeration systems which has COP ranging between 3-4. Large effort has been taking place to improve the performance of the adsorption system by experimenting with various system and operating parameters including various designs of adsorbent bed, hot\cooling fluid inlet temperatures, different types of working pairs, heat and mass transfer increasing techniques . Various thermal cycles such as heat recovery, heat and mass recovery, thermal wave and cascade cycle has been studied to improve the performance of the adsorption system. In this paper, mathematical modeling of two bed adsorption system has been modeled in the analysis of the system using the tooth adsorption isotherm model. Simulation programming in Microsoft Excel has been proposed for obtaining the results from data.

Keywords— **Adsorption ,Coefficient of performance, Low grade thermal energy, Mathematical modeling**

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I. INTRODUCTION

As the human comfort level increases, demand of the refrigeration and air conditioning increases day by day. According to the survey, it is estimated that energy consumption will be increased about 71% by 2030.Around 80% of energy on earth comes from fossil fuels. Hence, the awareness on decrease fossil fuel recourses, remote area problems and environmental issues leads to development toward new technologies. Use of abundantly available energies like wind, solar, biomass, hydropower, geothermal energies, even thermal waste from various process can be effectively utilized for fulfilling the demand of energy demands [1]. To mitigate the demand of air conditioning, conventional vapor compression refrigeration systems were commonly used. This system has been very popular due to their small size, low weight and higher performance value. However, Conventional systems were associated with disadvantage which leads to global warming and ozone layer depletion issue. Hydrochlorofluorocarbon (HFC) and chlorofluorocarbons (CFC) have been restricted in Montréal in 1988 and in Kyoto in 1998 conventions which are most responsible for ozone layer depletion and global warming problems. In Montréal(1988), some severe regulations were agreed to reduce ozone layer depletion. In Kyoto(1998) protocol, new regulations have been agreed for CFC, HFC and HCFC emission for controlling greenhouse gas emission [2].Another problem associated with conventional refrigeration systems is their large consumption of electrical energy which causes new investments, infrastructure, power plant and distribution lines for electricity network. As a result, worldwide, there is a strong need of alternative cooling technology that use sustainable and renewable energy supplies. The proper technology should be environmentally benign and provide high performance so that it can be compared with commonly used *vapour* compression cooling system. The adsorption refrigeration system is the best alternative for *vapour* compression systems which utilize low grade thermal energy for performing operations. A low grade thermal energy such as solar energy, exhaust from I.C engine are easily available. Adsorption system has some technical drawbacks such as low coefficient of performance , low specific cooling capacity, Poor heat and mass transfer capacity of adsorber bed leads to high cost and bulky system[2].However, this system is energy saving compared to conventional vapor compression systems which has simpler control, no vibration, no pollution, no noise, less operating and maintenance cost. This system contains less moving part leads to less complexity. The refrigerant used in the process is environmental friendly [3]. Hence adsorption system appear as alternative to integrate the conventional refrigeration system by more environmentally friendly systems which is powered by renewable energy source and bring sustainable development which fulfills the current international requirements. Researchers are working on adsorption system to improve the performance in order to overcome the economical and technical issues. Large research work is carried out on working pairs, different adsorption system models which are working for different operating conditions and the research on different types of adsorption cycle. There are various adsorption cycles such as basic cycles, heat recovery cycle ,mass recovery cycle, thermal wave cycle, cascade cycle etc.

The main objective of this paper is to investigate the performance of the adsorption refrigeration system powered by waste heat source by using the mathematical modeling of the system.

Jribi et al. presented work on activated carbon-CO_2 based adsorption refrigeration system for various range of hot inlet source temp and obtained the optimum results for temperature of 85°C. Simulation has been carried out for evaluation of the results and COP is obtained from the study is 0.100[4]. Ramji et.al presented comparative study of three different adsorbent-adsorbate working pairs using waste heat based on simulation. Author stipulated that activated carbon-water pair produce optimal cooling compared to methanol and ammonia. The COP obtained from the simulation for methanol and ammonia are 0.37 and 0.4 respectively and cooling capacity for methanol and ammonia are 0.65kW and 0.50kW respectively. Meanwhile, COP and cooling capacity for activated carbon-ammonia is 0.58 and 1kW respectively[6]. Wang et.al performed analysis of adsorption refrigerator using Calcium chloride-ammonia as working pair. Activated carbon is mixed with calcium chloride for enhancement of heat and mass transfer and increase cooling capacity of the system. The specific cooling power and coefficient of performance of the system were obtained 770.4W/kg and 0.39 respectively at evaporator temp is -20ºC[7]. Tiwari and Parishwad performed experimental work on adsorption system using activated carbon and ammonia. Author stipulated that adsorption capacity of ammonia at 60ºc is around 30% of the weight of the adsorber material. The COP obtained from this system is 0.5 for cooling capacity of 1kW[8]. Tamainot-Telo and Critoph experimentally investigated the thermo-physical properties of two types of monolithic activated carbon with intention of designing a high performance adsorber with ammonia as refrigerant. Almost all solid adsorbents are highly porous and this results in low density and very low thermal conductivity of adsorbent. Common method, to improve the thermal conductivity of the adsorbent is to use of consolidate adsorbent with high conductivity material like graphite, metallic foam [9].

II .ADSORPTION PHENOMENON

Adsorption is surface phenomenon occurring at the interface of refrigerant gas(gas phase) and adsorbent phase(solid phase) based on physical and chemical reaction. Adsorption occurs on the surface of substance is known as adsorbent and whose molecule gets adsorbed on the surface of adsorbent is known as adsorbate. When adsorbate (refrigerant) molecule fixed themselves at the surface of porous solid material (adsorbent) due to van der waals forces, this leads to accumulation of refrigerant on the surface of the adsorbent material known as physical adsorption. Desorption is a phenomenon in which substance is released from the surface of the adsorbent material due to heat provided.

II. DESCRIPTION OF THE ADSORPTION CYCLE

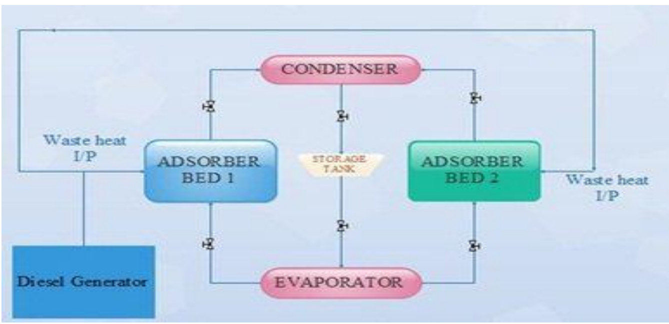

Fig1: Continuous adsorption cycle.

Fig 1 shows the schematic diagram of the two bed adsorption refrigeration cycle which consist of two adsorber bed, condenser, evaporator. Adsorbent materials are filled in the adsorber bed . At the starting point the Adsorber bed I is at low pressure and temperature with high refrigerant concentration within the adsorbent. During the starting of the desorption process when heat is applied by the heat source to the adsorber bed I, then the pressure of the adsorbent bed I is increases and the refrigerant is evaporated. When the pressure of the bed reaches to the pressure equal to the condenser which is the saturation pressure of the refrigerant then the valve between Bed I and condenser is opened. Evaporated refrigerant is cooled in the condenser by providing cooling water source. Then the refrigerant is expanded by using expansion value. And refrigerant is send in evaporator . The cooling water is provided for getting the cooling effect from refrigerant . Refrigerating effect is obtained at the evaporator outlet . During this process Adsorber bed I is heated. Now, Adsorber bed II is maintained at pressure and temp equals to the evaporator pressure for adsorption of the refrigerant on the adsorbent material. Similarly, the cycle is carried in same way as explained earlier.

IV. MATHEMATICAL MODELLING

1) Toth Isotherm:

Adsorption process is usually studied through graphs known as adsorption isotherms. Adsorption isotherms shows the curve which gives the adsorbed amount of refrigerant at the surface of the adsorbent at the constant temperature . At the low pressure, adsorption of the refrigerant takes place. At the high pressure when all sites of the adsorbent are fulfilled with the refrigerant and further increase in the pressure does not cause any difference in adsorption process. There are basic three types of the adsorption isotherms such as Langmuir, Freundilch and BET. Langmuir is the basic and important model used to describe the adsorption phenomenon on the homogeneous surface. In practical situation, the adsorption systems are heterogeneous so that the Langmuir model fails to describe the adsorption phenomenon.

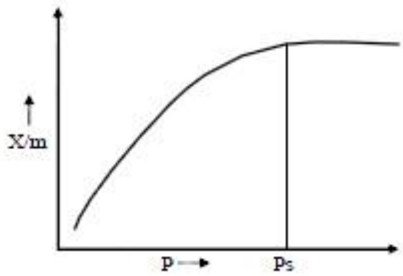

Fig 2: Basic adsorption isotherm.

Toth adsorption isotherm is commonly used to describe the adsorption phenomenon at the heterogeneous surface. Toth equation is used to describe the data of carbon oxides and hydrocarbons on zeolite and activated carbon in the field of surface chemistry and engineering.

$$C = C_O \frac{bP}{(1+(bP)^t)^{\frac{1}{t}}} \tag{1}$$

Where, C is the amount adsorbed at equilibrium pressure P and Co is the saturation adsorption capacity of the adsorbent for the gas. The parameter b is affinity constant. It describes that how strong an adsorbate molecule is attracted toward the surface of the adsorbent. In other words, it is solid- gas interaction parameter. The basic difference between Toth and Langmuir model is the parameter “t’’ which represents the heterogeneity factor . When “t’’ is reduces to the 1 the model behaves like Langmuir adsorption isotherm model. The source of the heterogeneity could be the solid or the adsorbate or a combination of both[10].

2) Heat of adsorption:

The isosteric heat of adsorption (Qst) is calculated from the following equation:

$$Q_{st=}RT^2\left(\frac{\partial lnP}{\partial T}\right) \tag{2}$$

Where Qst is isosteric heat of adsorption, R is the gas constant, T is the temperature of the system and P is the equilibrium pressure. Isosteric heat of adsorption is independent of surface coverage[5].

3) Desorber bed energy balance:

Desorber bed is heat exchanger which is the main component of the adsorption system. The input temperature from the heat source is given to the desorbed bed . Desorber bed contains the adsorbent and refrigerant . When the input heat from the heat source is given to the desorber bed, the refrigerant which is accumulated on the surface of the adsorbent is evaporated until the maximum desorption temperature is achieved in the desorber bed . The evaporated refrigerant is goes in condenser for condensation. During the desorption process the valve towards condenser is opened and valve which connects the evaporator is closed. The energy balance equation for desorber is given as follows:

$$(MC_p)_{bed}\frac{dT_{bed,des}}{dt} = M_{Adsorbent}\frac{dC_{des}}{dt}Q_{st} - (\dot{m}c_p)(T_{hot,in} - T_{hot,out}) \tag{3}$$

Where, $(MC_p)_{bed}$ is the mass and specific heat of the metallic parts of the desorption bed respectively. $\frac{dT_{bed,des}}{dt}$ is the rate of change of temperature w.r to time. $M_{Adsorbent}$is the mass of adsorbent in bed, Q_{st} is the Isosteric heat generated during the process, $\dot{m}c_p$is the mass flow rate and specific heat of the exhaust gas respectively. $T_{hot,in}$ is the temperature of the exhaust gas at inlet, $T_{hot,out}$ is the temperature of the heat exhaust at the outlet of the desorber bed[5].

The left hand side of the Eq (3) represent the rate of change of internal energy due to the metallic parts of the desorber bed during desorption. The first term at the right hand side of the equation represents the desorption heat during the process. Second term on the right hand side of the equation represents the total amount of heat provided by the exhaust of the diesel generator . The outlet temperature of the exhaust gas is calculated by the log mean temperature difference method.

$$T_{hot\ out} = T_{bed,des} + \left(T_{hot,in} - T_{hot,des}\right)\exp\left(\frac{-UA_{bed}}{(\dot{m}c_p)_{hot}}\right) \tag{4}$$

Where, $T_{bed,d}$ is the temperature of the desorption bed, T_{hot} is the temperature of the exhaust gas at inlet, UA_b is the overall heat transfer rate and area of the desorber bed, is the $\dot{m}$, mass flow rate and specific heat of the hot gas respectively.

4) Adsorber bed energy balance :

Adsorber bed is the another heat exchanger which is used to provide the continuous cooling cycle in the basic intermittent adsorption refrigeration cycle. After completing the first cycle, the refrigerant from the evaporator is send to the second bed which is attached to the system. The adsorber bed is need to be cooled and should be maintain at the evaporator pressure level. During this process, the refrigerant coming out from the evaporator in the gaseous form is adsorb on the surface of the adsorbent material. The heated adsorber bed is need to be cooled hence the cooling water is circulated from the adsorber bed for removing the heat and maintain the evaporator pressure level for adsorption of the refrigerant on the adsorbent. During this process the valve between evaporator and adsorber bed is opened and valve between evaporator and adsorber bed is closed. The energy balance equation for adsorber is given as follows:

$$(MC_p)_{bed}\frac{dT_{bed,ads}}{dt}=M_{Adsorbent}\frac{dC_{ads}}{dt}\left(Q_{st}+h_{bed,ads}-h_{evap,out}\right)-(\dot{m}c_p)\left(T_{cool,in}-T_{cool,out}\right) \quad (5)$$

Where, $(MC_p)_{bed}$ is the mass and specific heat of the metallic parts of the adsorber bed respectively. $\frac{dT_{bed,ads}}{dt}$ is the rate of change of temperature w.r to time. $M_{Adsorbent}$is the mass of adsorbent in bed, Q_{st} is the Isosteric heat generated during the process, $\dot{m}c_p$is the mass flow rate and specific heat of the cooling water respectively. $h_{bed,ads}$ is the enthalpy of bed adsorption bed, $h_{evap,out}$ is the enthalpy at the outlet of the evaporator. $T_{cool,out}$ is the cooling water outlet temperature $T_{cool,in}$ is the cooling water inlet temperature. The left hand side of the Eq(5) represent the rate of change of internal energy due to the metallic parts of the adsorber bed during adsorption. The first term at the right hand side of the equation represents the adsorption heat during the adsorption process. The second term on the right hand side of the Eq(5) represents the total amount of heat released to the cooling water upon adsorption. The cooling water outlet temperature is modeled by log mean temperature difference method is given by:

$$T_{cool,out}=T_{bed,ads}+\left(T_{cool,in}-T_{bed,ads}\right)\exp\left(\frac{-UA_{bed}}{(\dot{m}c_p)_{cool}}\right) \quad (6)$$

Where, $T_{bed,a}$is the temperature of the adsorption bed , $T_{cool}$is the temperature of the inlet of the cool water. UA_b is the overall heat transfer rate and area of the adsorber.
bed, $(\dot{m}c_p)_{cool}$ is the mass flow rate and specific heat of the cooling water respectively[5].

5) Condenser energy balance:

The condenser is water cooled shell and tube heat exchanger which liquefies the vapour refrigerant eliminating from desorber during desorption process, delivering the condensed liquid to the evaporator via expansion valve. The energy balance equation for condenser is given as follows:

$$(MC_p)_{cond}\frac{dT_{cond}}{dt}=M_{Adsorbent}\frac{dC_{des}}{dt}\left(h_{bed,des}-h_{cond}\right)-(\dot{m}c_p)\left(T_{CW,ou} \right. \quad (7)$$

$(MC_p)_{cond}$is the mass and specific heat of the material of the condenser, $\frac{dT_{cond}}{dt}$ is the rate of change of temperature w.r.to time, $M_{Adsorbent}$ is the mass of the activated carbon, $h_{bed,des}$ enthalpy of the desorption bed, $h_{cond}$is the enthalpy of the condenser, $\dot{m}c_p$ is the mass flow rate and specific heat of the cooling water, $T_{CW,out}$ is the cooling water at the outlet of the condenser, $T_{CW,in}$is the cooling water at the inlet of the condenser.

On the left hand side of the Eq (7). represents the rate of change of internal energy by the metallic parts of heat exchanger due to variation in the condenser. On the right hand side, the first term gives the latent heat of vaporization due to the amount of refrigerant desorbed from the desorption bed and the amount of heat that the liquid condensate carries away it leaves the condenser to evaporator , the final term represents the total amount of heat released to the cooling water. The condenser and desorber bed are always maintain at the refrigerant saturated vapor pressure. Using log mean temperature difference, the cooling water outlet temperature of the condenser heat exchanger is written as:

$$T_{CW,out}=T_{cond}+\left(T_{CW,in}-T_{cond}\right)\exp\left(\frac{-UA_{cond}}{(\dot{m}c_p)_{CW}}\right) \quad (8)$$

Where, $T_{CW,out}$ is the cooling water at the outlet of the condenser, $T_{CW,in}$ is the cooling water at the inlet of the condenser, T_{cond} is the temperature of the condenser, is the UA_{cond} overall heat transfer rate and area of the evaporator, $(\dot{m}c_p)_{CW}$ is the mass flow rate and specific heat of the cooling water[5].

6) Evaporator energy balance:

The evaporator is shell and tube heat exchanger which is used in the adsorption system. The main function of the evaporator is turn the liquid form of the refrigerant coming from the
condenser. In evaporator refrigerant is evaporated or vaporized in gas .Evaporator is connected to the adsorber bed which is maintain at the evaporator pressure .The evaporated refrigerant get adsorbed at the surface of the adsorbent in adsorber bed.
The energy balance equation for condenser is given as follows:

$$(MC_p)_{evap}\frac{dT_{evap}}{dt}=M_{Adsorbent}\frac{dC_{ads}}{dt}\left(h_{evap,out}-h_{evap,in}\right)-(\dot{m}c_p)_{chill} \quad (9)$$

Where, $(MC_p)_{evap}$ is the mass and specific heat of the material of the evaporator, $\frac{dT_{evap}}{dt}$ is the rate of change of temperature w.r.to time, $h_{evap,out}$ is the enthalpy of the refrigerant at the outlet of the evaporator, $h_{evap,in}$ is the enthalpy of refrigerant at the inlet of the evaporator, $(\dot{m}c_p)_{chill}$ is the mass flow rate and specific heat of the chilled water, is the $T_{chill,out}$ temperature of the chill water at the outlet of the evaporator, is the temperature of chill, $T_{chill,in}$ water at the inlet of the evaporator. The left hand side of the equation represents the internal energy due to the sensible heat of the liquid refrigerant and the metal of heat exchanger in the evaporator. On the right hand side, the first term gives the latent heat of evaporation for amount of refrigerant adsorbed , the second
term shows the cooling capacity of the evaporator.

The chilled water outlet temperature is given by:

$$T_{chill,out} = T_{evap} + (T_{chill,in} - T_{chill,out}) \exp\left(\frac{-UA_{evap}}{(\dot{m}c_p)_{chill}}\right) \quad (10)$$

Where, $T_{chill,out}$ is the temperature of the chill water leaving the evaporator, T_{evap} is the temperature of the evaporator, $T_{chill,in}$ is the temperature of chill water at the inlet of the evaporator, UA_{evap} is the overall heat transfer rate and area of the evaporator respectively, $(\dot{m}c_p)_{chill}$ is the mass flow rate and specific heat of the chill water[5]

7) Performance of the system:

The basic adsorption cooling cycle is intermittent cycle, continuous cycle their should be minimum two beds. The chilling capacity and COP of the system can be expressed by following equation:

$$Q_{chill} = \int_0^{t_{cycle}} \frac{\dot{m}c_{p\ chill}(T_{chill,in} - T_{chill,out})dt}{t_{cycle}} \quad (11)$$

Where, Q_{chill} is the cooling capacity of the system, $\dot{m}c_p$ is the mass flow rate and specific heat of the chill water, $T_{chill,in}$ is the temperature at inlet of the evaporator, $T_{chill,out}$ is the temperature at outlet of the evaporator and t_{cycle} is the time required for the one cycle[5].

$$COP = \frac{\int_0^{t_{cycle}} \dot{m}c_{p\ chill}(T_{chill,in} - T_{chill,out})dt}{\int_0^{t_{cycle}} \dot{m}c_{p\ hot}(T_{hot,in} - T_{hot,out})dt} \quad (12)$$

Where, $\dot{m}c_{p\ chill}$ is the mass flow rate and specific heat of the chill water, $T_{chill,in}$ is the temperature at inlet of the evaporator, $T_{chill,out}$ is the temperature at outlet of the evaporator and t_{cycle} is the time required for the one cycle. and $\dot{m}c_{p\ hot}$ is the mass flow rate and specific heat of hot water, $T_{hot,in}$ is the hot water inlet temp, $T_{hot,out}$ is the hot water outlet temp[5].

V.CONCLUSION

Adsorption refrigeration cycles are the best alternatives for the conventional vapour compression refrigeration systems. But COP of adsorption system is 0.3-0.5 which is very low compared to conventional systems. hence adsorption systems are not commercialized till date. More researches has been carried out for different working pair to enhance different adsorption cycles. Large research has been carried out for the improving the performance of the system by changing the system and operating parameters. For cyclic steady state performance of the adsorption system mathematical model has presented in the paper. And simulation of the system is proposed in Microsoft Excel for determine the overall performance of the system by changing different system parameters.

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